Optimization of Airport Surface Traffic:

A Case-study of Incheon International Airport

8 June 2017

Yeonju Eun*, Daekeun Jeon,

Myeongsook Jeong, Hyounkyong Kim,

Eunmi Oh, and Sungkwon Hong,

Korea Aerospace Research Institute

Hanbong Lee, Yoon Jung

NASA Ames Research Center

Zhifan Zhu

SGT, NASA Ames Research Center

AIAA Aviation 2017, Denver, CO, June 5-9 2017

Contents

Introduction

- Incheon International Airport (ICN) in South Korea
  - Surface congestion due to continuously growing traffic demands
  - Airport expansion project in progress
  - Growing need for CDM and controller decision support tool

- Research Purpose
  - SW Development of a decision support tool for IADS (Integrated Arrival, Departure, Surface) operation in ICN
  - Research collaboration between Korea Aerospace Research Institute (KARI) and National Aeronautics and Space Administration (NASA)

- Operational characteristics analysis
- Simulation model development and validation

→ **Presented in ATIO 2016**

↓

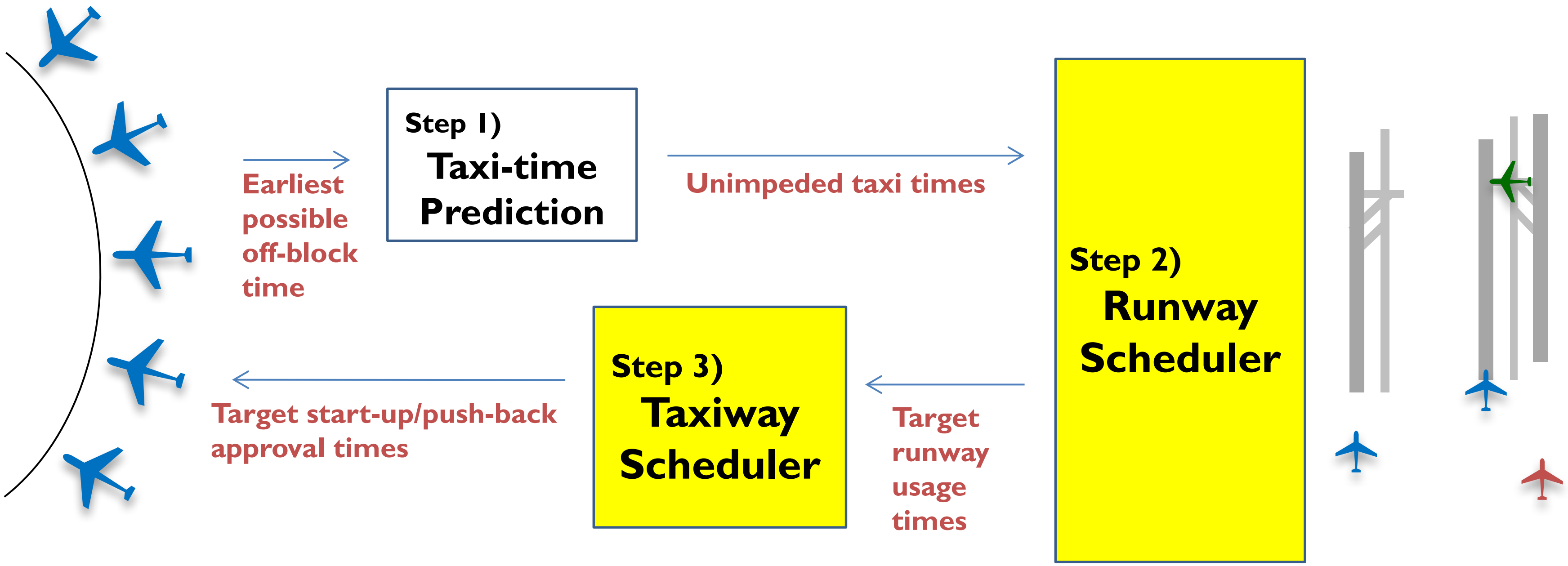
- Surface/departure scheduler SW development
- Simulation-based test environment development

↓

- Integrated test (including human-in-the-loop simulation)

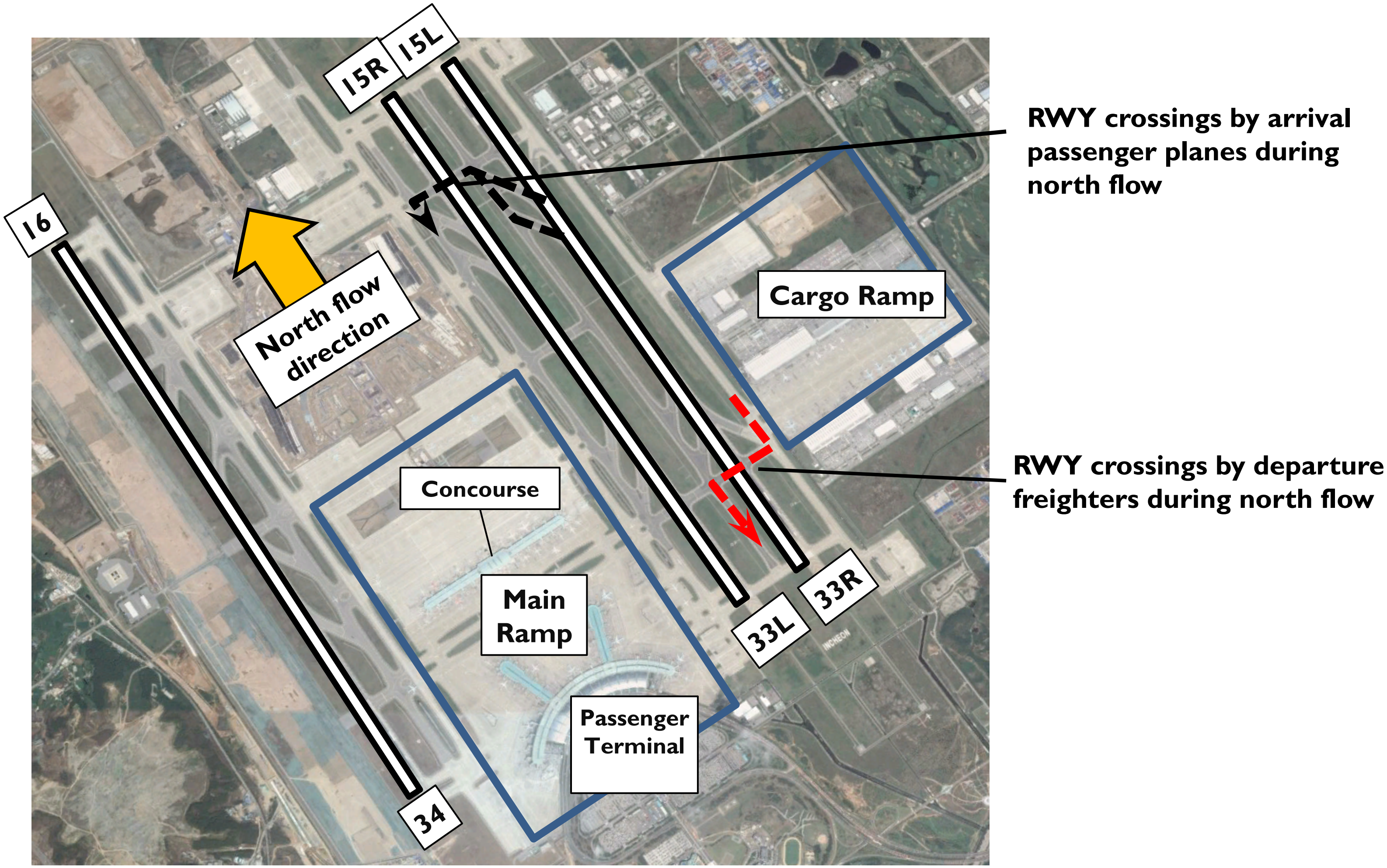
Introduction

- Research Direction
  - Based on 3-step approach



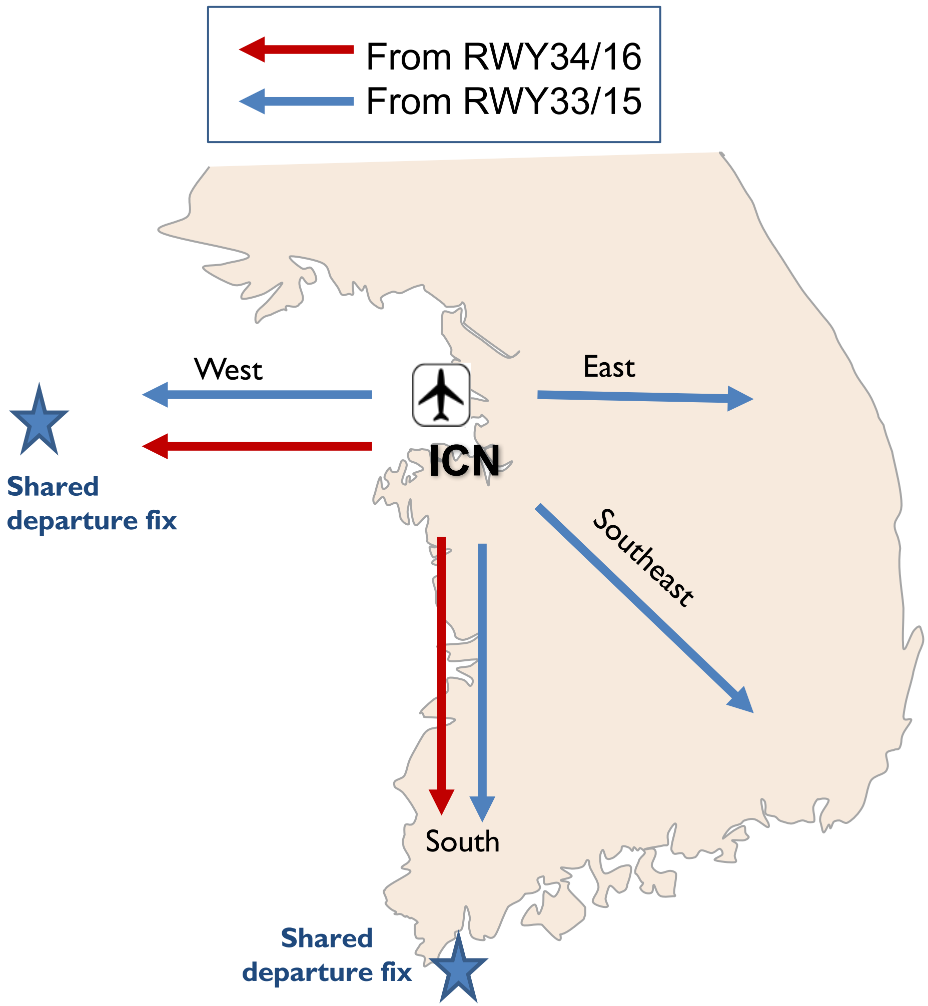
  - MILP-based optimization models were developed and tested.

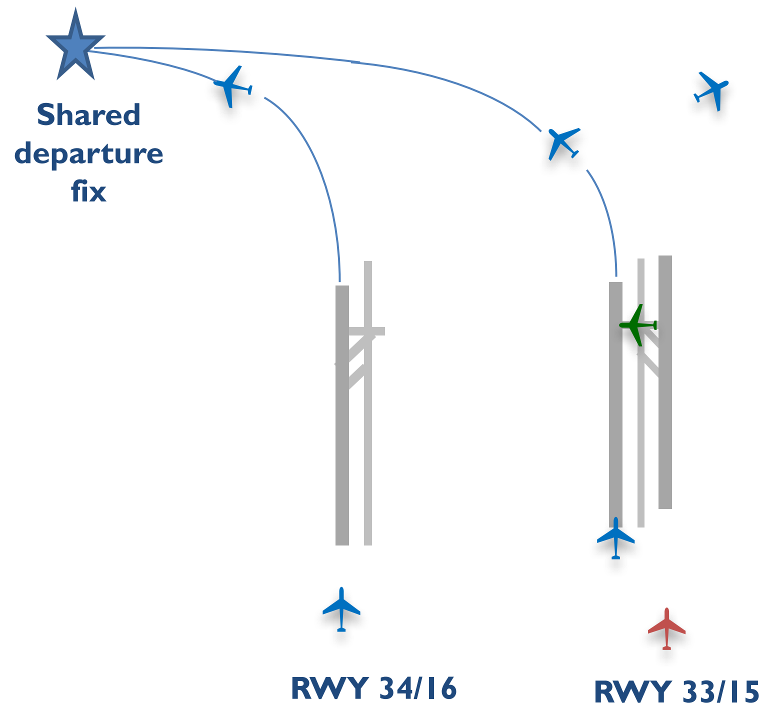
Scheduling Requirements



Airport Configuration

Scheduling Requirements

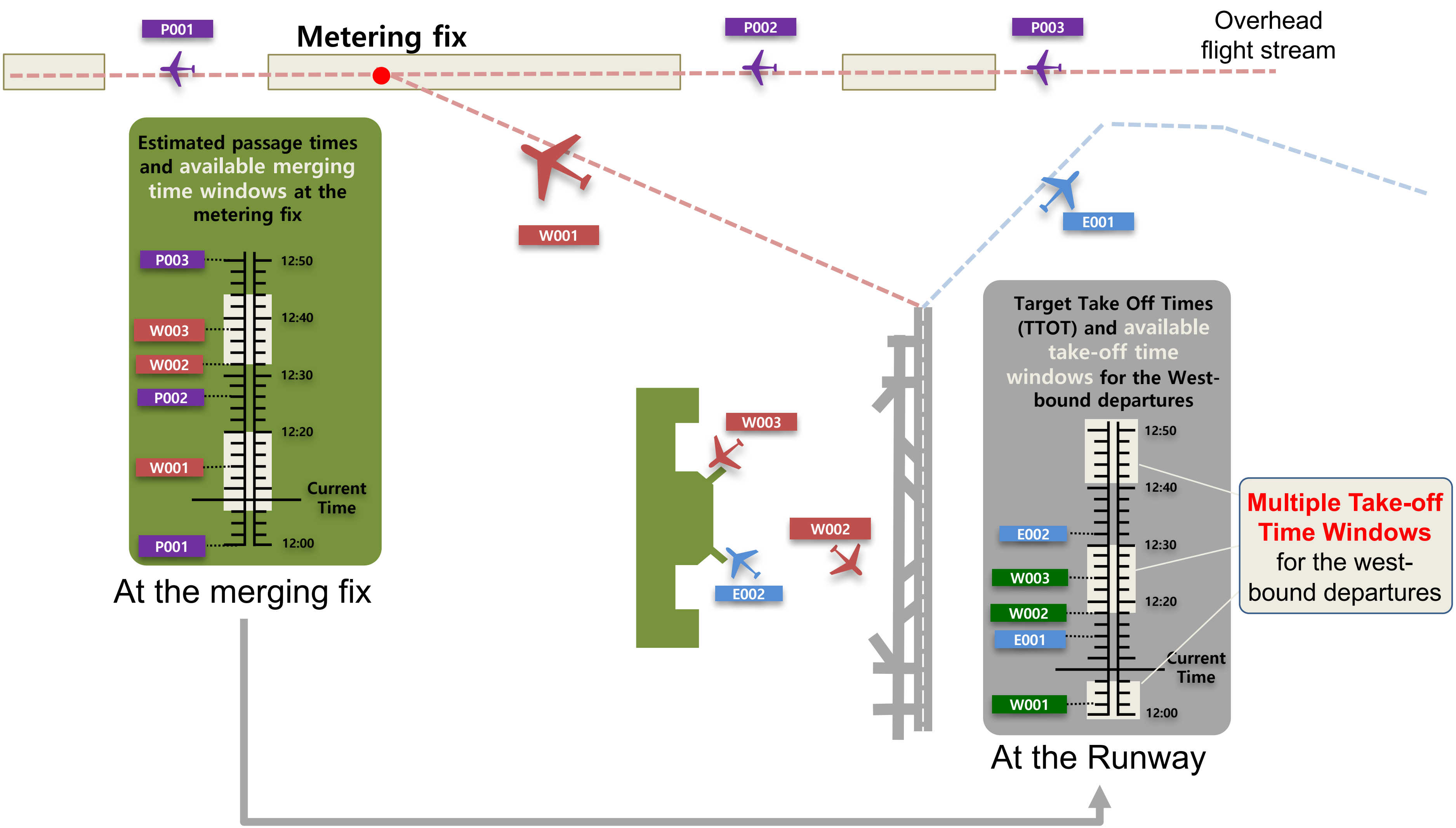




Departure route directions and a shared departure fix from the multiple runways in ICN

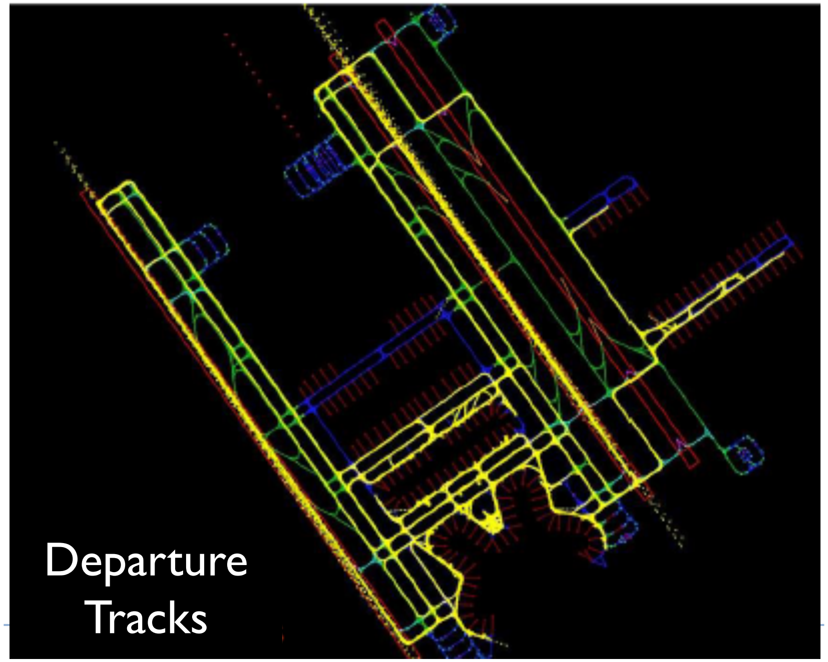
Scheduling Requirements

Multiple Take-off Time Windows



Scheduling Requirements

- Multiple runway scheduling
  - With shared departure fixes
- TMIs (Traffic Management Initiatives)
  - CFR
  - EDCT
  - MIT/MDI
  - Multiple takeoff time windows
- Runway crossings
  - Departure runway crossings by arrival flights
  - Arrival runway crossings by departure freighters
- Gate holding and pushback time limit
  - Earliest and/or latest takeoff time limit
- ELDT (Expected Landing Time)
  - Assumed to be given and not adjustable
- Taxi route of each aircraft
  - Assumed to be given and not adjustable



Runway Scheduling

$$\text{minimize} \quad \sum_{i \in D} \left(t_i - \text{EarliestT}_i \right)$$

$$\text{subject to} \quad z_{ij} + z_{ji} = 1, \;\; \forall i, j \in D \cup A \cup C, \; i \neq j$$

$$t_j - t_i - \text{Rsep}_{ij} \geq -M\left(1 - z_{ij}\right), \;\; \forall i, j \in D \cup A \cup C, \; i \neq j$$

$$\text{EarliestT}_i \leq t_i \leq \text{LatestT}_i, \;\; \forall i, j \in D \cup A \cup C, \;\; i \neq j$$

$$z_{ij} \in \{0, \; 1\}, \;\; \forall i, j \in D \cup A \cup C$$

$$z_{ij} = 1, \;\; \forall i, j \in D_{Class_k}, \;\; \text{EarliestT}_i < \text{EarliestT}_j, \;\; i \neq j$$

For ICN RWY scheduler,

$$\forall i \in D, \quad \begin{cases} \text{EarliestT}_i = \text{EarliestOffT}_i \\ \text{LatestT}_i = \text{EarliestOffT}_i + \text{MaxRunwayDelayT}_i \end{cases}$$

$$\forall i \in A, \;\; \text{EarliestT}_i = \text{LatestT}_i = \text{OnT}_i$$

$$\forall i \in C, \quad \begin{cases} \text{EarliestT}_i = \text{OnT}_i + \text{TransT}_i \\ \text{LatestT}_i = \min\left\{ \text{OnT}_j + \text{TransT}_j \,\middle|\, \forall j \in C : \text{OnT}_i < \text{OnT}_j \right\} \end{cases}$$

Runway Scheduling

<Additional Constraints for TMIs>

- **EDCT, CFR → Adjustment of EarliestT_i and LatestT_i**
- **MIT(Miles-In-Trail), MDI (Minimum Departure Interval)**

In case of MIT) $$t_j - t_i + \left(\text{TansT}_j^k - \text{TransT}_j^k - \frac{\text{MIT}_k}{\text{TransV}_i^k} \right) \geq -M\left(1 - z_{ij}\right), \quad \forall i, j \in D_{MIT_k}, \; i \neq j$$

In case of MDI) $$t_j - t_i + \left(\text{MDI}_k\right) \geq -M\left(1 - z_{ij}\right), \quad \forall i, j \in D_{MDI_k}, \; i \neq j$$

- **Multiple Take-off Time Windows**

$$TimeW_i = \left\{ \left[\text{MinTime}_{i,1}, \text{MaxTime}_{i,1}\right], \left[\text{MinTime}_{i,2}, \text{MaxTime}_{i,2}\right], \cdots, \left[\text{MinTime}_{i,N_{W_i}}, \text{MaxTime}_{i,N_{W_i}}\right] \right\}$$

$$s_i^k = \begin{cases} 1 & \text{if} \quad \text{MinTime}_{i,k} \leq t_i \leq \text{MaxTime}_{i,k} \\ 0 & \text{otherwise} \end{cases}$$

$$s_i^k \in \{1,0\}, \quad \forall i \in D_{TimeW}, \; k \in (1..N_{W_i}), \qquad \sum_{k=1}^{N_{W_i}} s_i^k = 1, \quad \forall i \in D_{TimeW}$$

Taxiway Scheduling

$$\text{minimize}\ \underbrace{\alpha_p \left(\sum_{i \in D, r \in R} \max\left[t_{i,r} - \text{DesiredOffT}_{i,r},\ 0\right] \right)}_{\textbf{Late Take-off Time}}$$

$$+ \underbrace{\alpha_d \left(\sum_{i \in D, r \in R} t_{i,r} - \sum_{i \in D, g \in G} t_{i,g} \right)}_{\textbf{Departure Taxi-out Time}} + \underbrace{\alpha_a \left(\sum_{i \in A, g \in G} t_{i,g} - \sum_{i \in A, r \in R} t_{i,r} \right)}_{\textbf{Arrival Taxi-in Time}}$$

subject to

$z_{ij}^{u} \in \{0,\ 1\},\quad \forall i, j \in D \cup A,\ \ i \neq j,\ \ u \in I$ **Passage sequence of flight i and j at node u**

$t_{i,u} \geq 0,\quad \forall i \in D \cup A,\ \ u \in N$ **Passage time of flight i at node u**

$z_{ij}^{u} + z_{ji}^{u} = 1,\quad \forall i,j \in D \cup A,\ \ i \neq j,\ \ u \in I$ **Passage sequence at node u**

$t_{i,v} \geq t_{i,u} + \text{MinTaxiT}_{uv},\quad \forall i \in D \cup A,\ \ (u,v) \in E$ **Minimum travel time in link u-v**

$z_{ij}^{u} = z_{ij}^{v},\quad \forall i,j \in D \cup A,\ \ i \neq j,\ \ u,v \in I,\ \ (u,v) \in E$ **No overtaking allowed along taxiways**

$z_{ij}^{u} + z_{ji}^{v} = 1,\quad \forall i,j \in D \cup A,\ \ i \neq j,\ \ u,v \in I,\ \ (u,v) \in E$ **Conflict free in bi-directional link**

Taxiway Scheduling

subject to (continued)

$$t_{j,u} - t_{i,u} - \left(t_{i,v} - t_{i,u}\right)\frac{\mathrm{Dsep}_{ij}}{l_{uv}} \geq -\left(1 - z_{ij}^{u}\right)M, \quad \forall i, j \in D \bigcup A, \ \ i \neq j, \ \ u \in I, \ \ (u,v) \in E$$

$$t_{j,v} - t_{i,v} - \left(t_{j,v} - t_{j,u}\right)\frac{\mathrm{Dsep}_{ij}}{l_{uv}} \geq -\left(1 - z_{ij}^{v}\right)M, \quad \forall i, j \in D \bigcup A, \ \ i \neq j, \ \ v \in I, \ \ (u,v) \in E$$

Maintaining required separations at intersections

$$t_{j,r} - t_{i,r} - \mathrm{Rsep}_{ij} \geq -\left(1 - z_{ij}^{r}\right)M, \quad \forall i, j \in D, \ \ i \neq j, \ \ r \in R$$ **Runway separation**

$$t_{i,r} \geq \mathrm{EarliestOffT}_{i,r}, \quad \forall i \in D, \ \ r \in R$$ **Earliest take-off time**

$$t_{i,g} \geq \mathrm{OutT}_{i,g}, \quad \forall i \in D, \ \ g \in G$$ **Pushback ready time**

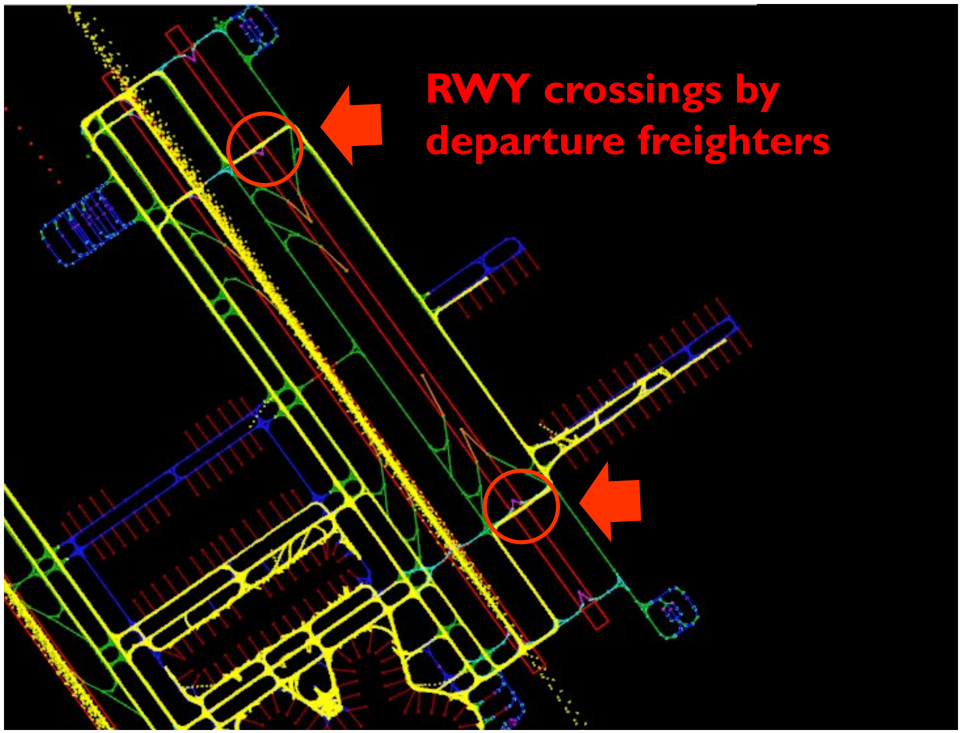
$$t_{i,g} \leq \mathrm{OutT}_{i,g} + \mathrm{MaxGateHold}_{i,g}, \quad \forall i \in D, \ \ g \in G$$ **Maximum gate holding time**

$$t_{i,r} = \mathrm{OnT}_{i,r}, \quad \forall i \in A, \ \ r \in R$$ **Arrival landing time**

$$t_{i,u} = \mathrm{FrozenT}_{i,u}, \quad \forall i \in D' \bigcup A', \ \ u \in N$$ **Frozen schedule**

Taxiway Scheduling

<Additional Constraints for RWY crossings >



Departure Tracks

C_{dep} : Set of departure freighters (which need to cross the arrival runway.)

$$C_{dep} \subset D$$

crossing sequence = departure sequence

$$z_{ij}^{c} = z_{ij}^{r} \quad \forall i, j \in C_{dep},\ i \neq j,\ \ r \in R$$

Runway separation with Arrivals

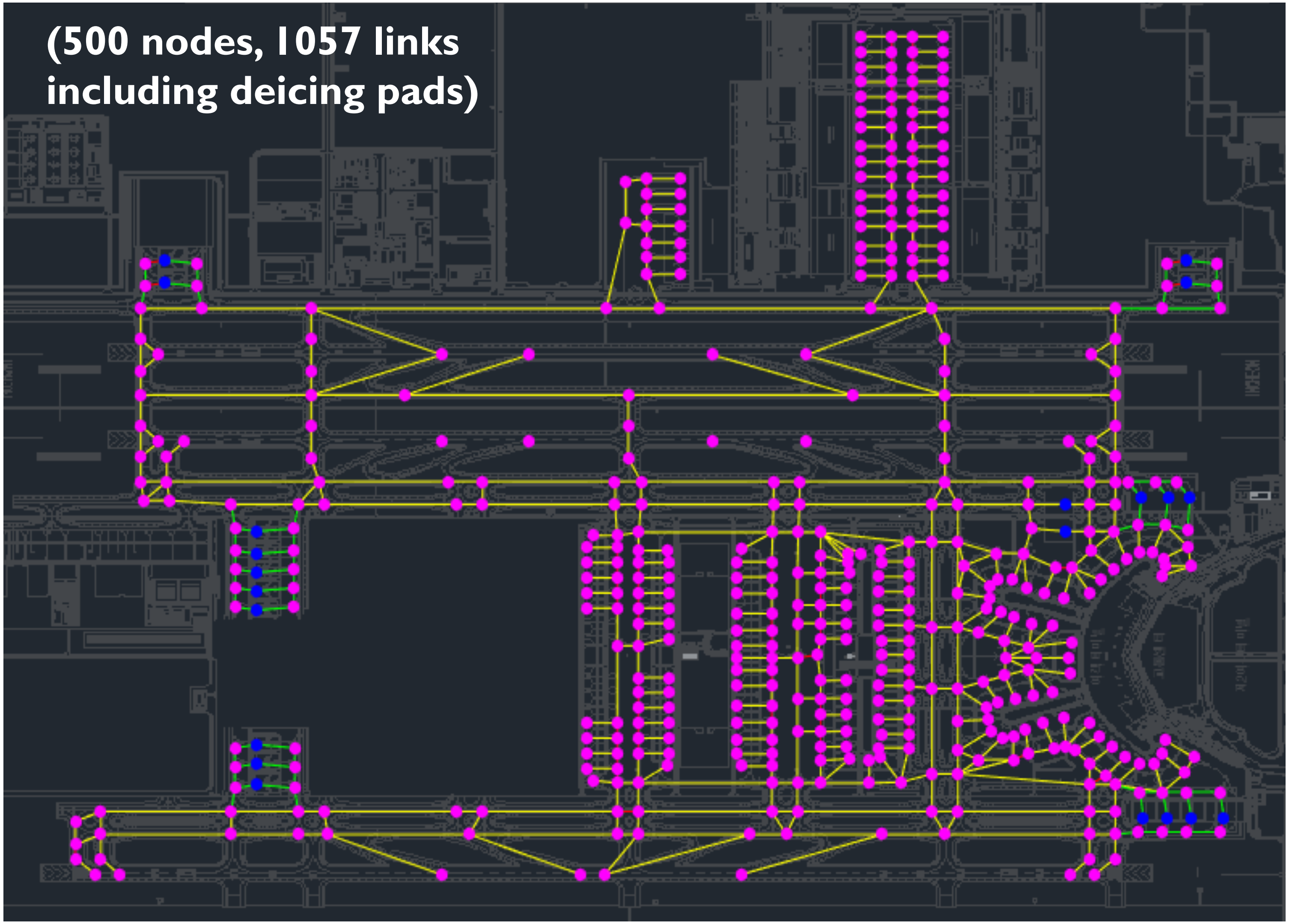
$$t_{j,r} - t_{i,c} - \mathrm{Rsep}_{ij} \geq -M\left(1 - z_{ij}^{crs}\right)$$

$$t_{i,c} - t_{j,r} - \mathrm{Rsep}_{ji} \geq -M \cdot z_{ij}^{crs}$$

$$z_{ij}^{crs} \in \{0, 1\}, \quad \forall (i, j) \in (C_{dep} \times A)$$

Taxiway Scheduling

ICN Node-link model for taxiway scheduling



Optimization Tests

RWY separation matrix

Separation between Dep and Dep (sec)

		Tailing Aircraft			
		L	M	H	S
Leading aircraft	L	120	120	120	120
	M	180	120	120	120
	H	180	180	120	120
	S	180	180	120	120

Dep	L	M	H	S
	80	52	45	45

Arr	L	M	H	S
	85	47	40	40

Crs	L	M	H	S
	30	30	30	30

RWY occupancy times (sec)

Separation between Dep and Arr : RWY occupancy time of a preceding aircraft + 10sec
Separation between Dep and Crs : RWY occupancy time of a preceding aircraft + 10sec

Separation between operations on independent RWYs : 0sec

Optimization Tests

- Single Scenario Test
  - Purpose) Optimization results check for both runway scheduling and taxiway scheduling.
  - Test Scenario) Based on the real operation data of April 2015, the number of departures was assumed to be increased by 30% from a normal traffic volume.

- Monte-Carlo Test
  - Purpose) Computation time performance check for the multiple runway scheduling problem.
  - Test Scenario) Number of departures and arrivals are assumed to be same with the current peak time operation. For each test case, 100 randomly generated scenarios were used.

Optimization Tests – single scenario test

Scenario)

48 departures + 12 arrivals during 09:00-10:00

- 19 departures + 12 arrivals + 9 crossings on RWY33/15
- 29 departures on RWY34/16
- 4 departures from RWY33/15 and 11 departures from RWY34/16 merge into same route (South-bound)

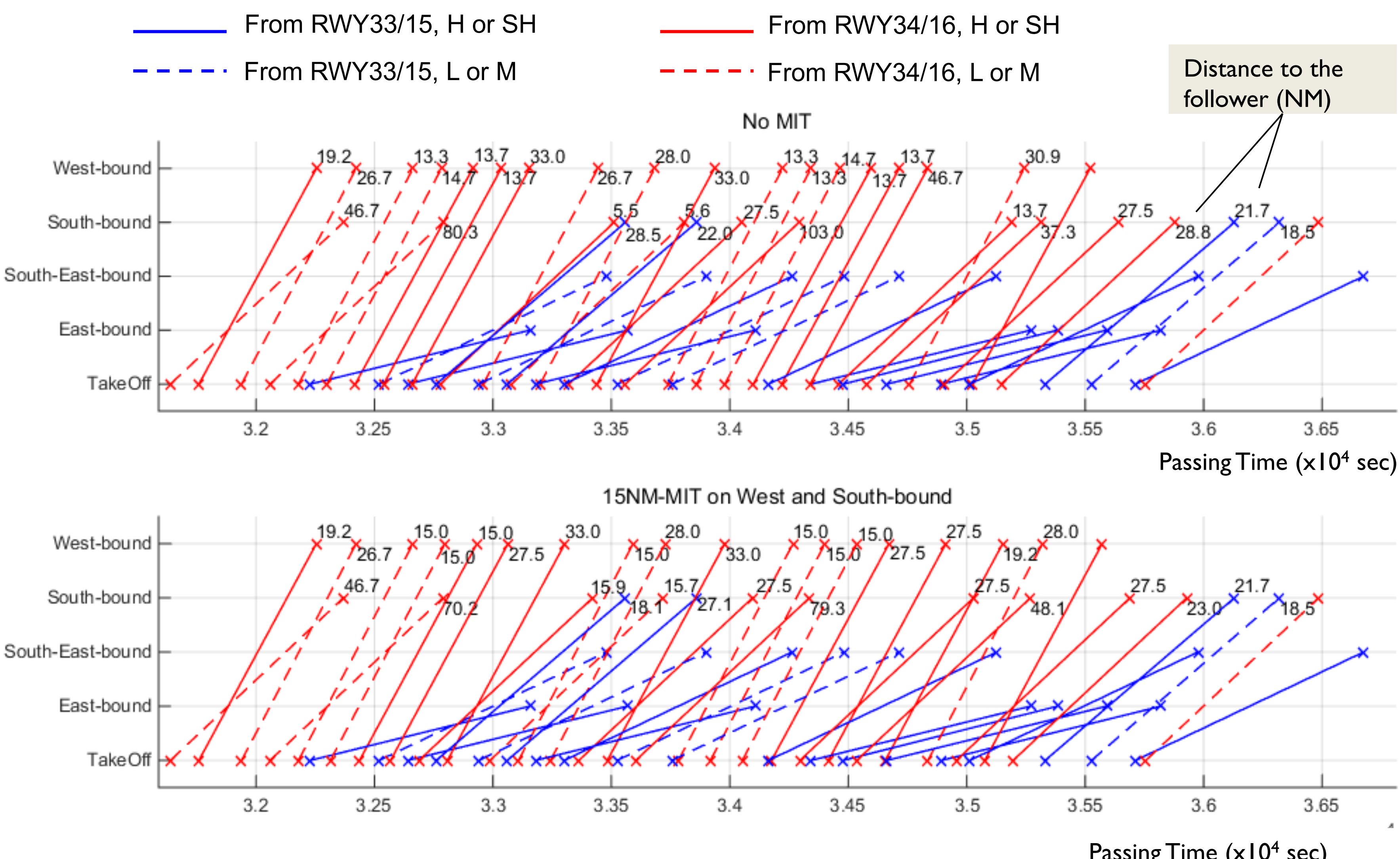
<table>
<tr><td rowspan="2">12
Arrivals</td><td rowspan="2">12 on
RWY33/15</td><td>L</td><td>M</td><td>H</td><td>S</td><td colspan="4" rowspan="2">9 PAX(RWY crossing accompanied)+ 3 CGO</td></tr>
<tr><td></td><td>3</td><td>9</td><td></td></tr>
<tr><td rowspan="3">48
Departures</td><td rowspan="2">19 on
RWY33/15</td><td rowspan="2"></td><td rowspan="2">5</td><td rowspan="2">13</td><td rowspan="2">1</td><td>W-bound</td><td>S-bound</td><td>SE-bound</td><td>E-bound</td></tr>
<tr><td>0</td><td>4</td><td>8</td><td>7</td></tr>
<tr><td>29 on
RWY34/16</td><td></td><td>13</td><td>16</td><td></td><td>18</td><td>11</td><td>0</td><td>0</td></tr>
</table>

Constraints)

CPS : 3

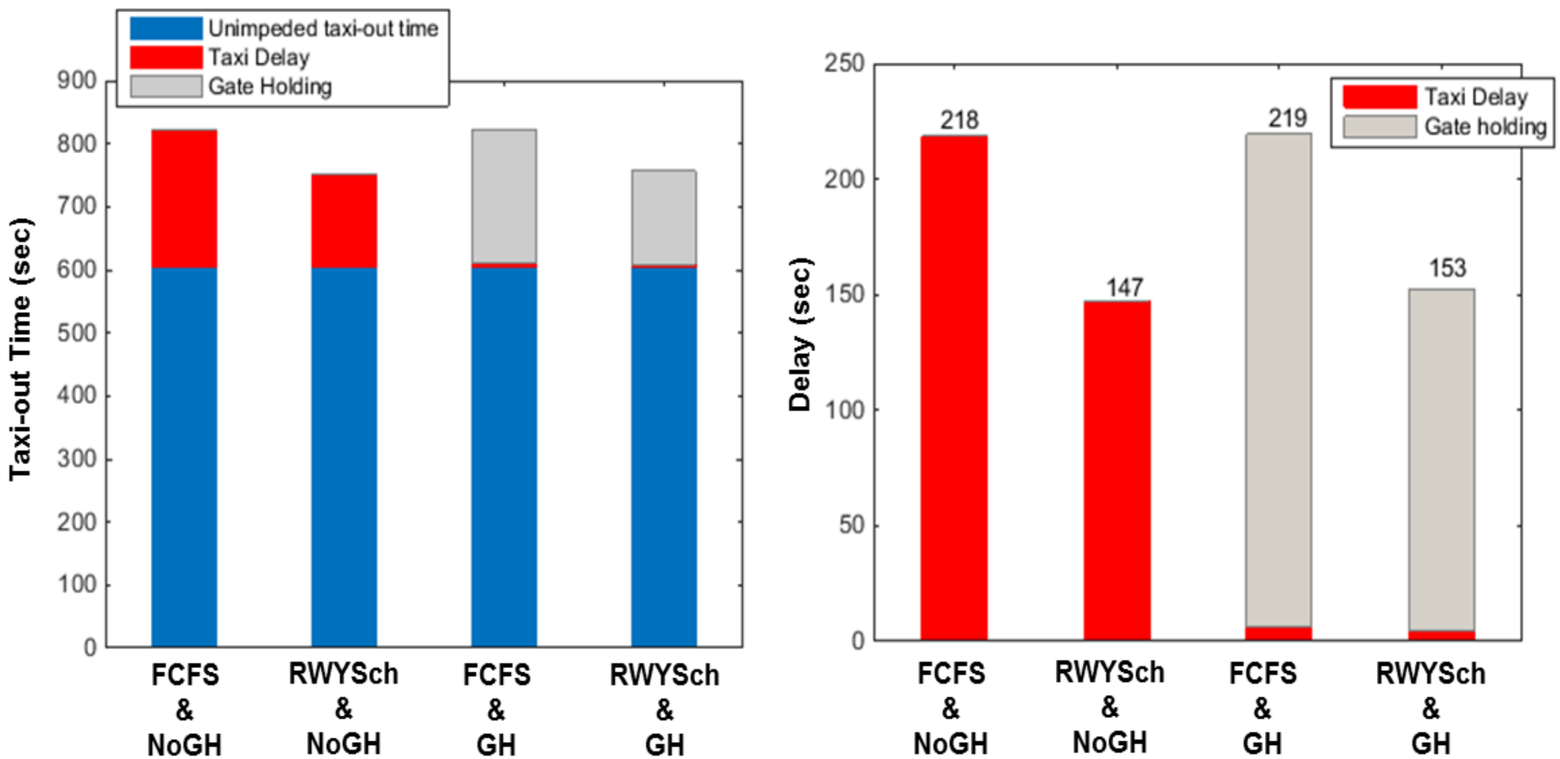
TMI : MIT on West-bound/South-bound

Optimization Tests – single scenario test



Passage Times and Separations at Departure Fixes

Optimization Tests – single scenario test

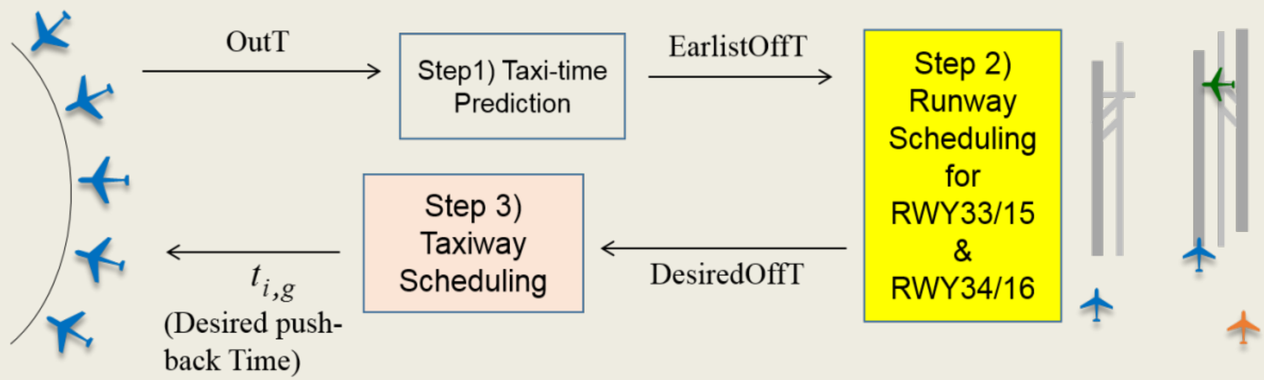


Averaged taxi-out time and delay per departure aircraft

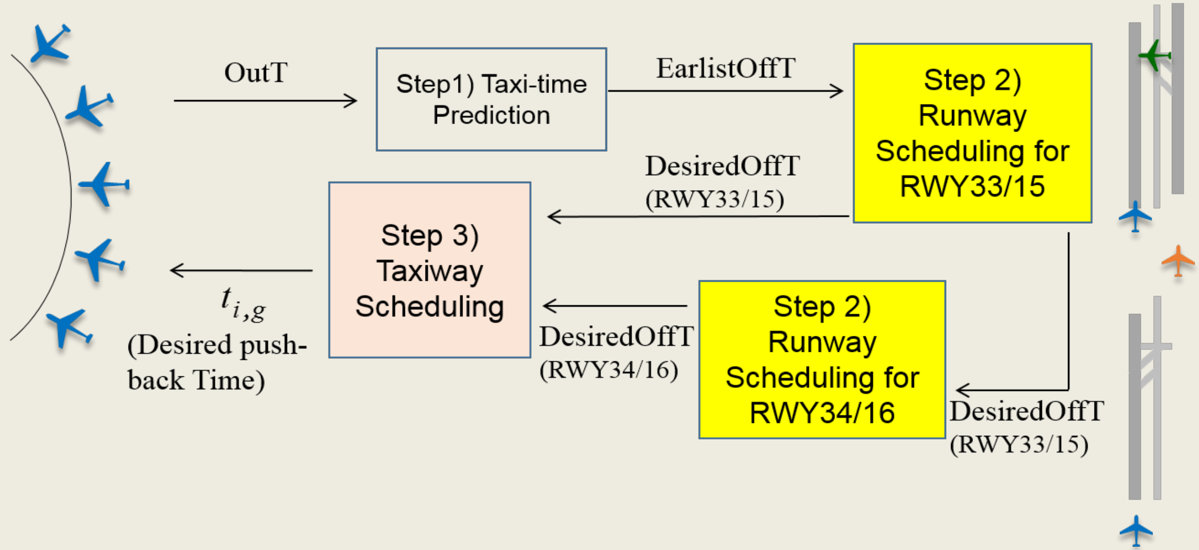
Optimization Tests – Monte-Carlo test

Two different methods for the multiple runway scheduling problem

Simultaneous optimization for the multiple runway scheduling



Sequential optimization for the multiple runway scheduling



Optimization Tests – Monte-Carlo test

Test scenarios

- 40 departures + 20 arrivals for 1 hour (the number of departure runways: 2)
- 15NM MIT separation on south-bound departures
  - Involves all south-bound departures from both runways to the shared departure fix.
- 100 random scenarios for each test case

	The total number of departures = 40	
	from RWY 33L/15R (to the shared fix)	from RWY 34/16 (to the shared fix)
Case 0	15 (5)	25 (10)
Case 1	14 (4)	26 (11)
Case 2	13 (3)	27 (12)
Case 3	12 (2)	28 (13)
Case 4	11 (1)	29 (14)
Case 5	10 (0)	30 (15)

- The total number of the south-bound departures to the shared departure fix are same.
- The south-bound departures which take-off from RWY 33L/15R were re-assigned to RWY34/16 one-by-one over case 0-5.

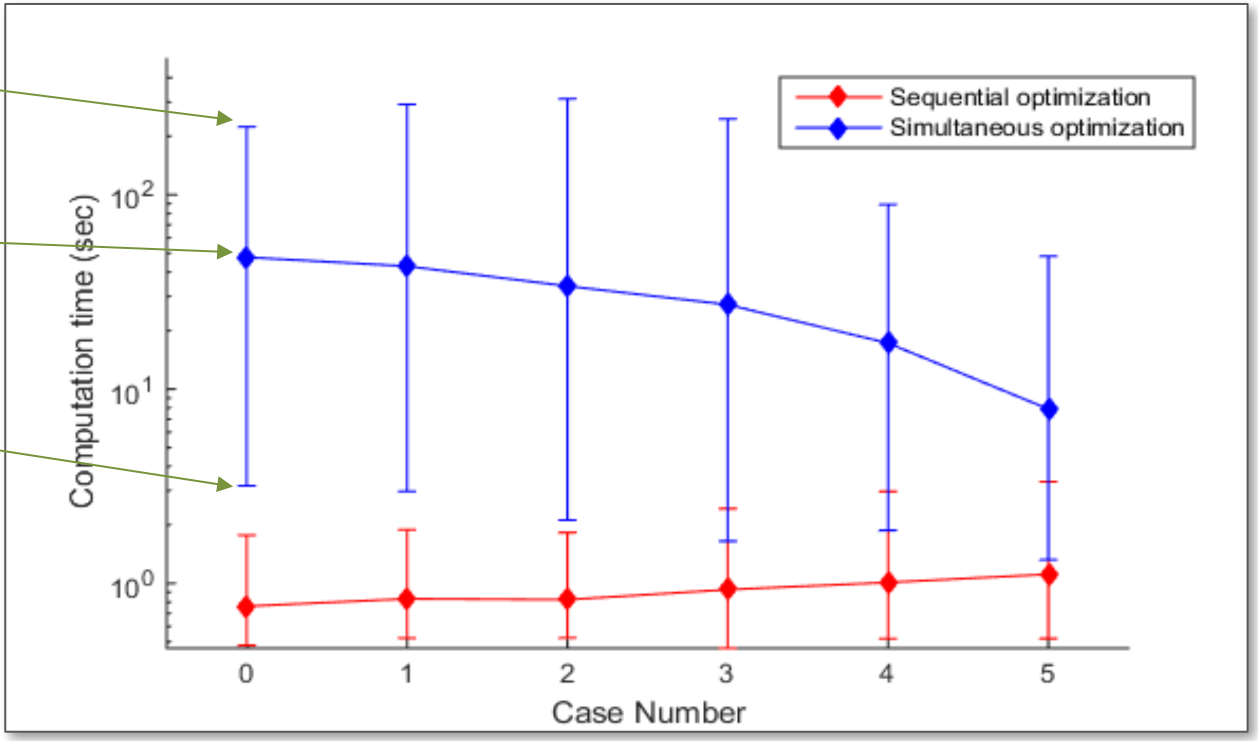
Optimization Tests – Monte-Carlo test

Test results: computation time comparison

90th percentile

Averaged computation time of 100 scenarios

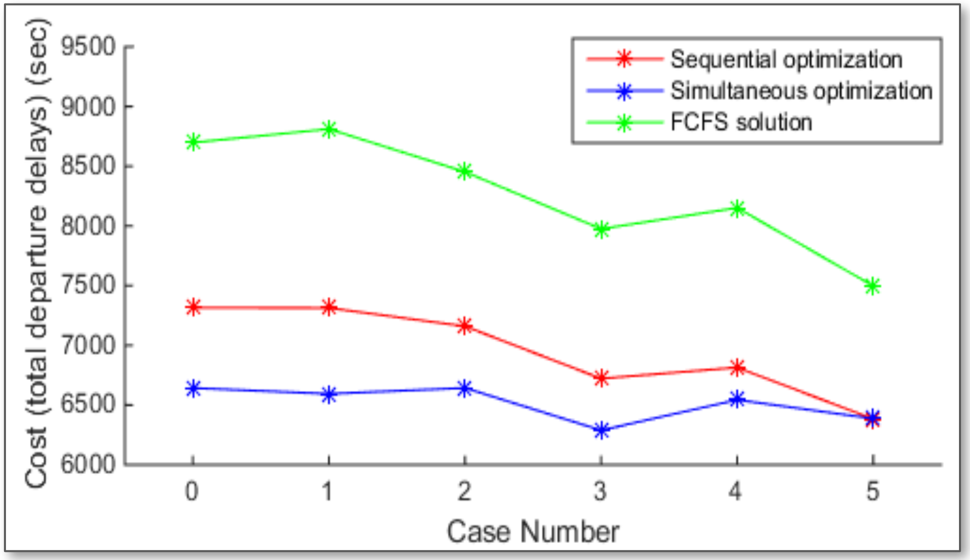
10th percentile



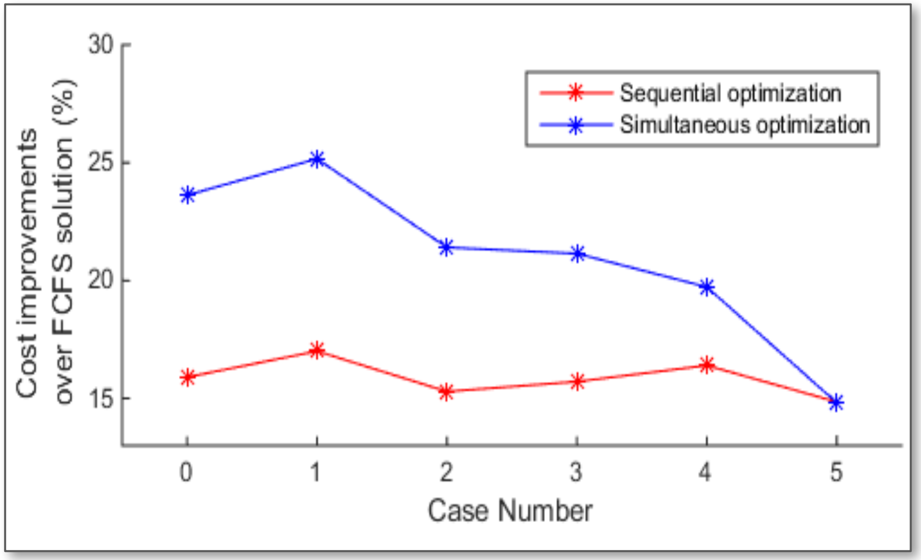
Computation time comparison in a log scale

Optimization Tests – Monte-Carlo test

Test results: Optimization cost comparison



Optimization cost comparison



Cost improvements over FCFS solution

Conclusion

- Developed the optimization models for airport surface traffic scheduling
  - MILP-based optimization models for runway scheduling and taxiway scheduling were developed and tested.
  - TMIs and operational characteristics which are specific to ICN were incorporated.
    - Multiple runway scheduling with consideration for MIT(Miles-In-Trail) separation at the shared departure fix
    - ‘Multiple take-off time windows’ constraints
    - Two different types of runway crossings on the coupled runways 33L/15R and 33R/15L.
- Suggested a method for better computation time performance
  - The sequential optimization using ‘multiple take-off time windows’ was proposed.
  - The sequential optimization shows much better performance with reasonably low cost for the multiple runway scheduling problem.
- Future Works
  - Integration of the additional requirements from ANSP (Air Navigation Service Provider) of ICN, such as cruise altitude assignment to the departure flights in pre-departure sequencing stage.
  - Runway assignment problem for runway balancing at an airport with multiple departure runways.

Thank You

Contact to: yjeun@kari.re.kr